Enlightening falsehoods: a modal view of scientific understanding

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1. Introduction

A great deal of scientific activity consists in constructing, comparing, and testing theories and associated models (TAMs) that are *known to misrepresent* the way the world actually is.[i] It is non controversial among scientists and even philosophers of science that these TAMs have epistemic value. The epistemic value of TAMs roughly comes in three kinds:

(1) predictive power,
(2) explanatory power,
(3) heuristic power.

First, notice that TAMs that misrepresent the world cannot be taken to provide explanations if one crucial characteristic of explanations is that the explanans statements be true, as it is the case in most accounts of explanation.[ii] Now, some of these TAMs have some predictive power, and that no doubt lends them some epistemic value. That said, most philosophers agree that this is not always the whole story, and for two main reasons. The first is that not all of the TAMs that are known to misrepresent the world are good at making predictions. The second is that most philosophers reject a purely instrumentalist view of science, and hope that TAMs that misrepresent the world can be conceived as affording some epistemic value beyond their mere predictive power.

Whether we are considering the extreme cases of TAMs that lack both explanatory and predictive power, or whether we are looking for some epistemic value "beyond" predictive or explanatory power, one option obviously remains open: TAMs that are known to misrepresent the world have heuristic power. They help scientists find theories and models that are either better at predicting, or better at explaining, or both.

One crucial question that arises at this point, but that has not been addressed in the literature, is: how do they do that? What is it about these TAMs that gives us the cognitive ability to move forward? What cognitive achievement do they foster that renders progress possible? Understanding. More precisely, I submit that TAMs that misrepresent the world afford a form of scientific understanding of their target phenomena. This form of scientific understanding is a cognitive achievement that lies at the core of the various degrees of heuristic power that TAMs that misrepresent the world can have.

In this paper, I will articulate a novel concept of scientific understanding. Roughly, the idea is that it consists in the ability to navigate some of the various *possible* worlds in which the phenomena arise. I dub this form of scientific understanding *modal understanding*. Section 2 will be devoted to developing this idea in more detail. Section 3 follows with answers to the most common objections that can be leveled against this "modal view" of scientific understanding. It will also address how modal understanding relates to extant views of scientific understanding: the claim will be that modal understanding includes these as special cases, but also goes far beyond them.

2. Modal Understanding

The basic idea behind modal understanding is simple. One gains understanding of the phenomena when one has some idea of how possibly the phenomena *might* arise. This includes the ways in which the phenomena might arise in this world and in other possible worlds as well. But this basic idea is just the beginning. There is much more to say.

Modal understanding is characterized as follows:

One has some *modal understanding of some phenomena* if and only if one *knows how to navigate some of the possibility space* associated with the phenomena.

Modal understanding encapsulates the basic idea insofar as knowing any possible way in which the phenomena arise provides one with modal understanding. It goes beyond this basic idea insofar as it introduces the idea of *knowing how to navigate a possibility space*. This is the crucial component of modal understanding that needs to be fully elaborated. This requires that we articulate the notion of a possibility space (2.2) as well as what is meant by navigating (2.3) such a space. The notion of a possibility space can be clarified by fixing on a domain of phenomena, i.e. a set of phenomena P and its subsets, and by appealing to the set possible worlds in which P, or some subset of P, is the case. Before we can start to elaborate on the notion of possibility space, the notions of set and subset of phenomena need immediate clarification, as the phenomena are not set-theoretical structures. Once this is clarified, the notions of possibilty space and of navigating such a space will be developed.

2.1. Phenomena and data sets

Following Woodward and Bogen[iii], let us first adopt here the fairly uncontroversial view according to which:

- the **phenomena** are stable, reproducible factual features of the world, for example:
    - lead melts at 327.5˚C., or
    - pressure increases with temperature for most fixed-volume gases;
- the **data** are records produced by measurement and experiment, that are intended to represent the target phenomena, for example:
    - a series of temperature readings as a piece of lead is heated up, or
    - a series of pressure readings as a gas confined in a container is heated up.

Following Woodward and Bogen, it is also admitted that the data reflect not only the phenomena, but also various extraneous factors associated with the idiosyncrasies of measurement apparatuses and contexts, and for which we typically have no systematic account. That said, it is also assumed that this is typically unproblematic. In most cases, scientists can "extract" from the data a *fair representation* of the phenomena. Finally, it is assumed that, for much of scientific practice, the data serve as evidence for the existence of the phenomena, and that TAMs are meant to account for the phenomena in systematic ways.[iv] So, in our examples: the series of temperature readings on the piece of melting lead is evidence for the fact that the melting point of lead is 327.5˚C, and the theory of phase transformation in metals aims at accounting for that fact, among others. Similarly, the series of pressure readings of a gas as it is heated provide evidence for the fact that pressure increases with temperature for most gases when the volume is constant, while the theory of gases is meant to account for that fact, among others.

With this framework in mind, it becomes clear that, while the phenomena are the target of TAMs, the data are what gives us a hold on the phenomena. Gathering data is a way for us to systematically investigate various aspects of the phenomena. While there is no way for us to cut out or conjoin portions of a phenomenon, there are straightforward ways to cut out, select, group, or exclude portions of the corresponding data set. So, it is slightly misleading to speak of the domain of a TAM as a set of phenomena. What we really should speak about is the set of data that is associated with the phenomena that the TAMs targets. In our example, the theory of phase transition includes in its target domain the melting point of lead, but also of many other metals and alloys, as well as other kinds of materials. While it is does not make sense to speak about a set of phase transition phenomena literally, it does make sense to speak about a data set of temperature readings on various melting metals and alloys, and other kinds of materials. Similarly concerning the theory of ideal gases, it is misleading to talk about the set of target phenomena, but it makes senses to speak about the data set of pressure readings for various contained gases as they are heated up. The same point can be made for the notion of a subset of phenomena.

To conclude on this, then: one can make sense of the idea that the target domain for a TAM is the set of phenomena and its subsets once we realize that our way to carve up the phenomena is via the data, and that the data can be understood as set-theoretical entities. Now that we have clarified these issues, we can turn back to the notion of 'possibility space' that appears in our characterization of modal understanding.

2.2. Possiblity Space

We start with a fixed domain P of phenomena, and its subsets, in the sense above. For example, we consider all of the gas behavior we observe in our world, or we consider the quantum, or astronomical phenomena. What is the possibility space associated with P?

The notion of possibility space is meant to be comprehensive. First, we consider the set S of possible worlds in which P, or some subset of P in the sense above, is the case. Next we consider the set of dependency structures that, when appropriately associated together, give rise to P, or to some subset of P, within S. The possibility space for P will be the set of dependency structures in those possible worlds that give rise to any subset of P *and the relations between those structures*. It is important to emphasize that the possibility space does not only include the set of possible dependency structures for P and the subsets of P: it also includes the *relationships* between these structures. This is important because the notion of *navigating* the possibility space will crucially relate to these relationships. More will be said on this below. For now, let us illustrate the notion of possibility space as just described with some examples.

Again, we start with a domain of phenomena P, the set S of possible worlds in which P, or some subset of P, is the case, and the set of dependency structures in S that, when appropriately associated together, give rise to all or some of P. Characterizing a dependency structure consists in the specification of some factors and some relations between these factors. Dependency relations are often causal,[v] such as the relation between a gravitational field and the gravitational force on a massive body located within the field. They can also be mereological, such as the relation between the total cholesterol, and HD and LD cholesterol. Finally, dependency relations can be logical, such as the identity between the morning star and the evening star. Dependency relations may, but need not, be described in mathematical terms. They may be static or dynamic. They may hold at all times, or only at specific times. One might want to include emergence relations as well, such as the relation between the mental state of pleasure and the underlying neuronal states. If so, then one might want to include not only bottom-up, mechanistic structures, but also top-down, high-to-low-level structures.[vi]

So, for example, taking the domain P_G of phenomena associated with gas behavior, we consider the set of dependency structures that, when appropriately associated, give rise to P_G, or to some subset of P_G, in the set S_G of possible worlds in which P_G, or some subset of P_G, is the case. One such dependency structure is, for example, that kinetic energy, associated with the mean speed of the molecules, contributes to the internal energy of gases.[vii] One dependency structure will typically be present in more than one world. One possible world containing the dependency structure above is a world in which gases are ideal gases: they are made of point masses between which all the collisions are perfectly elastic, and in which there are no intra-molecular forces. In such a world, all of the internal energy of gases is in the form of kinetic energy, so that any change in kinetic energy will result in a change in temperature. Another possible world would be one in which gases are as is described by the van der Waals model. In such a world, there still are no intra-molecular forces, but gas molecules are subject to long-range attractive *inter*-molecular forces (that keep the gas molecules together), and are non-zero size "hard balls". The strength of the attractive forces and the size of the molecules are respectively characterized by two constants, *a* and *b*, which are characteristic properties of particular gases. The parameter *a* is the molar volume. The parameter *b* is a measure of the strength of the long-range inter-molecular attraction forces: it varies a lot, and is stronger for polar molecules. Because of this, a particular gas in a "van der Waals" world will typically have higher volume and lower pressure than its counterpart in an "ideal gas" world. It will also typically have a higher boiling point, as the bonds between the molecules are harder to break down, due to the attractive forces. In the "van-der-waals" worlds the kinetic energy contributes to the total internal energy of gases together with the potential energy associated with attractive forces. In other words, the dependency structure relating speed of molecules, kinetic energy, and internal energy, is embedded in a larger dependency structure, which also includes the dependency structure relating long-range attraction, potential energy, and internal energy.

With this example in mind, one starts to understand in what sense dependency structures can be said to have *relations*. Some dependency structures can be embedded in larger ones. Some can share none, some, or all factors. Some can share some factors, but the relationships between these factors might differ. Typically, different dependency structures will give rise to different subsets of P. In our example, the dependency structures as described in the ideal gas and in the van der Waals theories give rise to different subsets of P_G. Notably, the subset of phenomena to which the ideal gas theory gives rise is included in the subset of phenomena to which the van der Waals theory gives rise. This obviously derives from the relations between the dependency structures described by each of the theories.

An interesting case is found when distinct dependency structures give rise to the same set of phenomena. In other words, we find ourselves with TAMs that describe distinct dependency structures, compatible with distinct (possibly exclusive) classes of worlds, and yet they are empirically equivalent theories. A situation like this is found in the quantum mechanical case.[viii] It is uncontroversial that we have at least two distinct TAMs that recover all the non-relativistic quantum mechanical phenomena equally well: Everett quantum mechanics and Bohmian quantum mechanics. These TAMs can be each associated with a class of worlds: the "Everettian" worlds and the "Bohmian" worlds. All of these worlds have some structure in common, corresponding to the wave function, and its deterministic evolution as described by Schrödinger Equation. That said, these structures are integrated into very different kinds of dependency structures according to whether they are in Bohmian, or Everettian worlds.

In the Everettian worlds, the wave function represents a fundamental ontological entity. Wave function evolution is governed by the Schrödinger Equation. The wave function determines which worlds[ix] are emergent at the phenomenal level.[x] When an experiment is carried out on a quantum system, all the possible outcomes associated with the wave function are realized, each in an emergent world. In the Bohmian worlds, by contrast, the wave function does not represent an entity but is rather nomological (Dürr et al., 1997): it governs the motion of the fundamental entities: the particles. The particles are characterized by their position, and Bohmian mechanics prescribes how these positions evolve over time. Note that Bohmian mechanics does include not only the wave function and the Schrödinger Equation, but also the Guiding Equation, which governs the evolution of the configuration of the particles.[xi] As a result experiments have single, deterministic, outcomes in Bohmian worlds.

It should be clear at this point that the common formalism of the wave function and the Schrödinger equation are integrated into very different kinds of dependency structures in the Everettian and the Bohmian worlds. Here again, it makes perfect sense to talk about how distinct dependency structures *relate* to one another. While some structural features are shared by Bohmian and Everettian worlds (e.g. that the evolution of the wave function is governed by the Schrödinger equation), the dependency structures in which some of these common structures are embedded are divergent, and arguably incompatible.

At this point, the reader should have a good grasp on what is meant when we define the possibility space for P as the set of dependency structures in those possible worlds in which any subset of P is the case *and the relations between these structures.* For example, the possibility space associated with gas behavior includes, among others, the dependency structures found in the ideal gas worlds, the ones found in the van der Waals worlds, and the relations between these dependency structures. Similarly, the possibility space associated with (non-relativistic) quantum phenomena includes, among others, the dependency structures found in the Everettian worlds, the dependency structures found in the Bohmian worlds, *and the relations* between these structures. With this in mind, we can finally turn to the last piece needed to explicate the notion of modal understanding, i.e. to what we mean by *navigating* a possibility space.

2.3 Navigating the possibility space

Remember that having some modal understanding was characterized as **knowing how to navigate** some of the possibility space associated with the target phenomena. What does that mean?

First, consider know-how. There are some serious attempts at making sense of what it means to know how to do something in epistemology. That said, the debate in epistemology mostly focuses on whether or not all forms of know-how are reducible to, or dependent on, forms of propositional knowledge.[xii] This particular issue is irrelevant to the argument of this paper. It will be sufficient to adopt a fairly uncontroversial view of know-how as an epistemic state that manifests itself as an ability or skill. Let us say more about the nature of the ability that is involved in the case of modal understanding.

The nature of the ability associated with modal understanding is crucially tied to the notion of "navigating" (some of) the possibility space for some domain of phenomena P. There are at least three distinct levels at which one can know how to navigate a possibility space. The most basic level is knowing how a particular dependency structure gives rise to P, or to some subset of P. An additional level comes from knowing how various dependency structures are *related* to one another. Finally, a third level consists in knowing how some overall constraints apply to the entirety of the possibility space. Let us say more about each of these levels.

The basic level of navigation skills, and hence of modal understanding, is associated with knowing how a particular dependency structure D gives rise to P or to some subset of P. . This involves knowing how the group of factors and the relations between these factors, which together characterize D, can be instantiated in some worlds and together give rise to the subset of phenomena it recovers. Some of the ways in which such ability can manifest itself include the ability to answer "what-if-things-had-been-different-questions" or w-questions, as Woodward (2003) has dubbed them,[xiii] and/or a form of epistemic resilience that allows one to appeal to the workings of the dependency structure within some world(s) to justify their views when pressed with critical questions, and/or yet again the ability to generalize and transfer, i.e. to recognize the dependency structure as a "type" of structure, and to successfully transfer that type to other instances in other contexts, to construct models of the phenomena, and/or possibly other ways as well. Overall then, modal understanding at this level consists in knowing how to navigate the inner workings of a particular dependency structure within some possible world(s). Immediately it is clear that modal understanding admits of degrees. The more dependency structures for which one knows how they give rise to some subset of P, the more understanding is afforded of P. The more worlds one knows in which some dependency structure can be present and give rise to some subset of P, the more understanding one has of the phenomena. Additionally, within the class of dependency structures for P, some afford more understanding than others insofar as they capture a larger subset of P.

Knowing how to navigate a possibility space consists in more than this. An additional dimension to understanding comes from knowing how various dependency structures that give rise to some subset(s) of P are *related* to one another. For example, one might know how, when instantiated in some worlds, different dependency structures are complementary, or incompatible, etc. One might also know how to modify one structure so that a similar structure is instantiated in some world(s) in which a larger subset of the phenomena is the case than in worlds in which the original structure is instantiated, or how to modify the structure to make it compatible with another one. Again, some of the ways in which modal understanding can manifest itself include the ability to answer w-questions, some form of epistemic resilience, the ability to generalize and transfer, and possibly others. Overall then, at this second level, modal understanding consists knowing how to navigate between various structures within the possibility space.

Finally, a third level of navigation skills within the possibility space for P consists in knowing how some general constraints apply to the entirety of the possibility space. In other words, it consists in knowing how some general features (if there are any) need to be shared by all dependency structures that give rise to the phenomena. For example, one might have a sense of the boundaries of the possibility space, i.e. one might know how some kinds of dependency structure are, or are not, possible. Or one might know how certain symmetries must be respected by all dependency structures. Or one might know how certain laws of conservation must be respected by all dependency structures. As for both previous levels, some of the ways in which modal understanding at this level manifests itself include the ability to answer w-questions, some form of epistemic resilience, the ability to generalize and transfer, and possibly others. Overall, this level of modal understanding consists in knowing how to navigate structural features of the possibility space itself.

Let us illustrate these three levels of navigation with some examples. Consider first again the possibility space associated with gas behavior. The first level of navigation consists in knowing how a dependency structure can give rise to some subset of P. So, one has some modal understanding for example if one knows how the dependency structures described by the ideal gas theory can be instantiated in some ideal-gas worlds and give rise to some of the target phenomena. This involves, among other things, knowing how the fundamental tenets of the kinetic molecular theory of gas play together to recover some of the behavior of well-diluted gases within the "normal" range of temperature and pressure. One also has some modal understanding if one knows how the dependency structures described by the van der Waals model can be instantiated in various van-der-waals worlds and give rise to some subset of the target phenomena. This involves, among other things, knowing how the basic properties of hard spheres, including the hard sphere potential, can recover gas behavior when the density is not so low. The subset of the phenomena being the case being larger in the van-der-waals worlds than in the ideal-gas worlds, one can say that one has, at least along that dimension, a higher degree of modal understanding in the later case than in the former case. One also has more understanding if one knows how both of these dependency structures can be instantiated in different worlds and give rise to different subsets of the phenomena.

Now, one reaches a *second level* of modal understanding if one *also knows how diferrent dependency structures for P relate to one another*, that is to say, one knows what the worlds in which these dependency structures are instantiated have in common (e.g. that kinetic energy contributes to internal energy), how they differ (e.g. how they differ on whether or not the size of the molecules and long range attraction are part of the picture, and how that changes the composition of internal energy), and the consequences (if any) this has on the subsets of the target phenomena that are recovered. For example, one knows how taking into account inter-molecular interactions allows to better recover gas behavior at lower temperatures, i.e. when the kinetic energy is not high enough to "trump" the potential energy, or at lower densities, i.e. when molecular interaction is higher. One also knows how the van der Waals dependency structure account for the existence of phase transitions, and of a critical point, beyond which no transition occurs.

Finally, a *third level* of navigation is reached when one knows how some constraints apply to all possible dependency structures for the phenomena. In our example, one would know how the four laws of thermodynamics apply to all of the possibility space for gas behavior. For example, one could know how the ideal gas law cannot apply at low temperature since it would be otherwise in contradiction with the 3rd law of thermodynamics, which states that entropy approaches zero when the temperature approaches zero (at the thermodynamic limit). Now the equation for the energy (U) for ideal gases is:

$U = 3/2\ PV = 3/2\ NRT$; where P is the pressure, V the volume, N the amount, R the gas constant, and T the temperature.

It follows that:

$(\partial U/\partial T)_V = 3/2\ NR$,

which obviously does not approach zero when the temperature approaches zero. Nor then does the entropy, given that the entropy for an ideal gas is:

$S = (3/2)\ Nk \ln U$. (where k is the Boltzmann constant)

Let us turn to the quantum domain, which turns out to be an interesting domain of application for the notion of modal understanding. This is partly because the question of how theories of quantum mechanics provide us with some understanding of quantum phenomena is notoriously difficult to answer, but it is easy to do so under the modal view.

Consider the set P of (non-relativistic) quantum mechanical phenomena. Modal understanding arises at a first level from knowing how a particular dependency structure can be embedded in a world and give rise to P. So, one has some modal understanding of P if one knows how the dependency structure in Everettian worlds gives rise to P. This involves, among other things, knowing how all possible outcomes of an experiment are realized in emergent worlds and how this is compatible with our subjective experience of only one of those outcomes being realized. This is done by explicitly including an observer into the dependency structure associated with the phenomena. Now one also has some modal understanding of P if one knows how the dependency structure in Bohmian worlds gives rise to the phenomena. This involves, among other things, knowing how including the particles and their motion in the picture provide an asymmetry that allows for any given experiment to have only one outcome instead of many. Of course, modal understanding at the basic level already comes in degree. Given that both Everettian and Bohmian quantum mechanics recover P equally well, there is no difference in degree of modal understanding between the two that solely depends on how much of the phenomena are saved. That said, one who knows how both the standard and the Bohmian dependency structures give rise to the phenomena has a higher degree of modal understanding than someone who knows only how one of them applies.

The second level of modal understanding is reached from knowing how distinct dependency structures are related. In our case, this clearly involves knowing how including either an observer, or the particles and their motion into the picture, yield very distinct dependency structures, both recovering the same set of phenomena, but one yielding single outcomes, the other multiple outcomes, for experiments. It also involves encouraging comparisons, and rising the question of whether, for example, the wave function is best interpreted as representing an evolving entity or as a law of evolution for more fundamental entities in the possible worlds associated with quantum mechanical phenomena (Allori, 2013).

Modal understanding finally arises at a third level from knowing how some overall constraints apply to the totality of the possibility space. The quantum case provides again a very nice illustration of this point with Bell's theorem. [xiv] Bell's theorem establishes that no theory that is both local and determinate can recover all quantum mechanical phenomena. In other words, any theory representing a dependency structure such that experiments have single outcomes must also have non-local features, and any theory rejecting non-local influences cannot represent experiments as having single outcomes. It a remarkable result, which can be seen as putting some boundaries on the possibility space for quantum phenomena. It tells us something about the kind of dependency structures that could or could not give rise to quantum mechanical phenomena. As such, it generates modal understanding. What is interesting here is that Bell's theorem does not provide us with a theory. It has neither predictive, nor explanatory power for the phenomena. It does not unveil the properties of a particular theory either. Rather, it describes a very general structural constraint on the possibility space associated with quantum mechanical phenomena. Under the modal view, this provides us with some understanding of the phenomena because, as we just explained, it allows us to gain some knowledge of how to navigate the possibility space. Note that the case of Bell's theorem is not isolated. In fact, a significant portion of foundational work in quantum physics precisely consists in inquiring which overall principles put the right kinds of constraints of the possibility space for quantum phenomena. Work on symmetries, and symmetry breaking, in physics also falls under the same category (Castellani 2013). Another area of research that comes to mind is the work done on quantum gravity. Consider for example the case of Quantum Loop Gravity: the idea is to build a theory of quantum gravity on the basis of General Relativity, by applying a well-known quantization process, which is applicable only if the theory is given an Hamiltonian formulation; the options for building Quantum Loop Gravity thus directly depend on some overall constraints on the possibility space (Wüthrich 2013). The modal view makes easily sense of that kind of foundational work in the sciences.

2.4. Modal Understanding, navigating power, and epistemic value

With a decent grasp on the modal view, we can now address the questions raised in the introduction in a novel way: what exactly does the epistemic value of TAMs that misrepresent the world consist in? If the answer is "some kind of heuristic value", what is it about these TAMs that give them such heuristic value?

Under the modal view, TAMs that misrepresent the world have epistemic value because afford navigating power: they provide us with some understanding of the phenomena by providing us with some knowledge of how to navigate the possibility space. They can do so at three different levels: by teaching us how a dependency structure can give rise to (some of) the target phenomena, by teaching us how distinct possible dependency structures for (some of) the target phenomena relate to one another, or by teaching us how some very general constraints apply to all possible dependency structures for (some of) the target phenomena. In so far as knowing-how has genuine, intrinsic, epistemic value, TAMs that have navigating power have genuine, intrinsic, epistemic value.

Additionally, TAMs that have navigating power have heuristic value. Modal understanding of TAMs includes understanding some of their limits, for example in terms of how much of the phenomena they can recover, as we have seen, for example, with the ideal gas model. Once the relation between the particular dependency structure represented within the model and the specific subset of phenomena recovered is recognized, the ways in which the model can be changed to recover a larger portion of the phenomena may become clearer. Thus van der Waals' model improves in that regards on the ideal gas law by including inter-molecular interactions into the picture. Modal understanding also allows for generalization and transfer. Knowing how to navigate a dependency structure may help us to recognize it as a *type* of dependency structure (e.g. an oscillator harmonic, or a inversed square law), and facilitate the application of that same type of structure to different contexts. Because we know how to navigate the dependency structure, we may be able to recognize better in which contexts such transfer is likely to be fruitful. Knowing how to navigate the possibility space for the target phenomena may also amount to recognizing some common structure between the various dependency structures at hand. This may help us figure out whether such common structure is a necessary part of all possible dependency structures, which obviously is a valuable piece of information for future research, or, whether including such common structure is accidental, or results from some arbitrary assumptions, which might be altered to open some new avenues for research. Those are some of the ways in which modal understanding, navigating power, and heuristic power come together.

Let us conclude then. Much scientific practice consists in the exploration of the possibility space for the phenomena. On the modal view this has intrinsic epistemic value because it provides us with genuine understanding of the target phenomena. This will likely be challenged in various ways. We hope to address some of the major concerns in the next section.

3. Questions and Answers

3.1. Is it really "understanding"?

There is no agreed upon definition of "understanding" among epistemologists. That said, a quick look at the literature reveals that most epistemologists agree on several characteristics of understanding:

- The most common ways in which understanding is taken to manifest itself are through the ability to infer, generalize, and transfer, as well as some form of epistemic resilience. These are also typical "measures" of understanding among psychologists. Modal understanding very clearly fits the bill here.
- Other properties of understanding agreed upon among epistemologists are that (1) understanding comes in degrees (possibly unlike knowledge), and (2) understanding is not easily transmissible (again, possibly unlike knowledge). Now, modal understanding obviously comes in degrees, and along various dimensions. Next, the kind of navigation skills which modal understanding consists in clearly belongs to the kind of skills the acquisition of which requires personal engagement and extensive practice, just like any any other instance of know-how.

- A significant portion of epistemologists characterize understanding as a cognitive achievement, which in turn is defined as a cognitive success due to the performance of an ability (Pritchard 2009, 2014). Here again, modal understanding fits the bill: any success associated with modal understanding will be due to the performance of the ability to navigate the possibility space.

To conclude, modal understanding is a very good candidate as an instance of understanding, given what the epistemologists and psychologists have to say about it.

3.2. Isn't it merely "internal" understanding?

One might want to make the following objection: modal understanding is a form of "internal" understanding, not a genuine form of understanding of the phenomena (Strevens 2013, Mizrahi 2012). Forms of internal understanding consist in understanding of the *inner workings* of TAMs. They provide us with knowledge of how TAMs yield the predictions that they do (Strevens 2013). For example, one might have some understanding of how phlogiston theory predicts that some material will burn. According to these authors, this will not, however, amount of genuine understanding of combustion. In Strevens' words: "It would be correct to say that historians of science understand the phlogiston theory well, but wrong to say that the phlogiston theorists understood combustion well." (Strevens 2013, 513) In fact, according to Strevens, the object of understanding in this case is solely the TAMs, not the phenomena. Strevens suggests that genuine understanding of the phenomena only occurs if one has a grasp of a *correct* explanation for the phenomena, which he dubs the "simple view" of scientific understanding.

The distinction between understanding of the inner workings of a theory and genuine understanding of the phenomena is important. That said, to answer the objection above, one has to consider another important distinction between two concepts that seem to be conflated across the board in the above discussion. That distinction is between understanding *the phenomena* and understanding *the world*.

By understanding the world, it is meant understanding what the world *is actually like*. By understanding the phenomena, it is meant understanding the way the world *appears* to us. Clearly, one way to understand the way the world appears to us (to understand the phenomena), is to understand how these phenomena actually arise in the world (to understand the world). That said, the salient feature of the phenomena is that they can arise in *many possible ways* besides the particular way in which they *actually* arise in the world. In fact, any theory that saves the phenomena describes a way in which the phenomena could possibly arise. Just because a theory is empirically successful, it does not follow, however, that it describes the particular way in which the phenomena actually arise in the world.

The case of incompatible but empirically equivalent theories should bring this point home. Because such theories are incompatible with one another, not all of them can be describing the particular way in which the phenomena *actually arise* in the world. At most one, if any, of these theories can possibly provide the correct explanation for the target phenomena. Now, because the theories are all empirically successful, they still can be said to each describe a particular way in which the phenomena *could arise* in the world. As a result, the question of whether or not any of these theories provides us with any understanding *of the world* is straightforward: at most one, if any, could possibly do so. Now the question of whether or not such theories can afford some form of understanding *of the phenomena* is a distinct question. That question is far less straightforward, that is, *unless one assumes that understanding the phenomena is only afforded via understanding of the world*. Arguably though, making such an assumption would simply be question begging, since it simply forbids any other form of scientific understanding of the phenomena. Once one recognizes the distinction between understanding the phenomena and understanding the world, the question of how one gains understanding the phenomena opens in new ways.

Now the objection above is that instances of modal understanding are *merely* instances of internal understanding of a theory, and that internal understanding of a theory does not provide any genuine understanding of the phenomena. In light of the above, it is clear that the objection is incomplete unless it is explained why internal understanding can never lead to understanding the phenomena. That it is not properly characterized as understanding the world is clear. That said again, it would be question begging to insist that understanding the world is the only way to understand the phenomena.

Now the notion of modal understanding in precisely articulated in such a way that it is explained how it is a form of understanding of the phenomena. Consider the case in which one does not have understanding of the actual world, but has modal understanding of the phenomena. That is, one knows how to navigate the possibility space for the phenomena. Now bear in mind that the target of our analysis concerns understanding the *phenomena*, *not the world*, and that the phenomena can arise in many ways that are different from the particular way in which they actually arise in the world. What gives rise to understanding of the world is that a theory describes some dependency structures giving rise to the target phenomena, and that such a description stands in an relation of adequacy with the actual world. What gives rise to modal understanding is that a theory describes some dependency structures giving rise to the target phenomena, and that such a description stands in a relation of adequacy with a possible world. Since, again, our target is understanding the phenomena, the latter seems just as appropriate as the former.

Here is another way to make the same point. All parties would seem to agree that understanding how some actual dependency structures in the world give rise to some phenomena provides genuine understanding, and not merely internal understanding. Suppose there is another dependency structure that gives rise to the phenomena in another possible world. If that possible world were actual, all parties would agree that it would afford understanding. The only difference in understanding in those cases is given by which world is actual. Now, again, insofar as we are interested in understanding the *phenomena* and not only understanding the *world*, *we should arguably be indifferent* in those cases. So, we should consider that modal understanding affords genuine understanding of the phenomena, even when it is not understanding of the world.

3.3. Does this imply that the simple view is flawed?

The simple view is incomplete, because, while it captures some instances of scientific understanding, it also excludes some important cases. As we shall explain below, it is likely that instances of understanding under the simple view – henceforth "S-understanding" – turn out to be instances of modal understanding. That said, the notion of modal understanding goes far beyond and is more comprehensive.

According to the simple view (Strevens 2013), one understands a phenomenon just in case one grasps a correct explanation for the phenomenon. Given this characterization, one can see that, depending on what is meant by "grasping", instances of S-understanding may or may not be instances of modal understanding. In his paper, Strevens provides some examples to explain what is meant by "grasping". One of these examples concerns understanding (some of) the chemistry of H_2O. One could know a few facts about water being made of oxygen and hydrogen, but, in Streven's view, that is not sufficient to count as understanding. By contrast, "understanding most of the properties of H_2O requires an appreciation of the *relation* between the hydrogen and oxygen atoms in an H_2O molecule" (my emphasis)(511). What to "appreciate a relation" exactly means is not very clear at this point. Here is how Strevens specifies what he means:

> *These cases show that the sort of grasping needed for understanding requires a more intimate acquaintance with the structure of the explanation than sometimes accompanies mere knowledge. It is not enough to know that one or more parts of, or conditions for, a correct explanation hold; their holding must be directly mentally apprehended. Understanding that is the name for this direct apprehension." (511)*

So, under the reasonable assumption that "direct apprehension" of how the parts of an explanation hold together includes knowing how to navigate the dependency structures that are characteristic of the explanation, then instances of S-understanding will also qualify as instances of modal understanding.

Now, of course, many instances of modal understanding will *not* qualify as instances of S-understanding. This is because modal understanding is afforded by possible explanations in addition to correct explanations. The question of why instances of modal understanding that are not instances of S-understanding qualify as instances of genuine understanding has been answered in the previous sections (3.1, 3.2).

Now, the advantages of a more comprehensive view of scientific understanding are at least three fold:

(1) the modal view easily assesses if, and explains how, TAMs that misrepresent the world provides us with genuine understanding of the phenomena – which they don't afford under the simple view;
(2) this, in turn, offers a way to characterize the nature and assess the degree of heuristic power afforded by these TAMs – on the other hand, on the simple view, why TAMs have heuristic power is not clear;[xv]
(3) the modal view is neutral towards the scientific realism debate – the simple view, on the other hand seems inappropriately tied to a commitment to scientific realism.

To put it bluntly, the mistake that Strevens makes is to focus too much on the *correctness* (of the explanation) and not enough on the *grasping* component of understanding. The consequence is that the view is tied to some form of scientific realism and excludes large portions of scientific activity from the sphere of scientific understanding. Both seem highly unwelcome.

3.4. Isn't it the case that the correct explanation will always afford the highest degree of understanding?

Not necessarily. First off, notice that the question trades on the conflation between understanding the world and understanding the phenomena. The intuition that the answer is "obviously yes" is correct *only if* the focus is on understanding the *world*. If we focus instead on understanding the phenomena, then the answer is not obvious anymore. Let us look into it.

Consider two empirically equivalent theories A and B for some domain of phenomena P, A providing the correct explanation for P, but not B. Experts on both sides know how to navigate the dependency structures associated with their theory, and how they recover P. Looking first at the two theories independently, I don't see what argument could be made to the effect that, somehow, knowing how to navigate the actual dependency structure affords more understanding of *the phenomena*, than knowing how to navigate the possible one. Again, on both sides, experts can equally well navigate the dependency structures described by their theory.

Now, one might want to say that having the correct explanation in hand is superior if one considers not the first, but the second level of modal understanding, i.e. understanding of the relations between dependency structures. How would that work? Consider again A and B, two empirically equivalent theories for some domain P. There is certainly understanding to be gained by knowing how the two dependency structures described by A and B relate to one another. That said, I fail to see what kind of argument could be made to the effect that, somehow, the actual dependency structure provides more understanding of the relations between the two than the other one. Understanding must be symmetric here: knowing how theory A relates to theory B is the same as knowing how theory B relates to theory A.

Now one might want to consider a further situation, in which we have not only theories A and B, but also theory C, also empirically equivalent. Some relationships hold between A and C, as well as between B and C. Next one would want to make the argument that, somehow, because A describes the actual dependency structure, understanding the relations between A and C is superior to understanding the relations between B and C. Again, I fail to see what that argument could look like.

Maybe at this point one could argue that, because A describes the actual dependency structure, "things are going to be easier" when we enlarge the set of phenomena, and unify various theories. The intuition would be that given some piece of truth, all other things being equal, it is more likely to jive with other theories one has around. I fail to see why that would be the case. If there is an empirically equivalent world to ours, then we are just as likely to hit on the truth as on empirical equivalent theories. In fact, if there are multiply empirically equivalent worlds, then it is more likely that we will have other theories around that will not fit with the truth. So, I don't think one could make the factual claim that truth will fit better with other theories around. Granted, it might be the case that, if a certain class of theories were more likely to fit with other extant theories, then they could afford more understanding; but, again, this class is not going to be the true theories, simply because there is no a priori reason to believe that extant theories describe the actual world instead of empirically equivalent ones.

So, I fail to see a compelling argument to the effect that correct explanations are necessarily conducive of the highest degree of understanding of the phenomena. I will grant that the intuition is strong though, and I think that this can be explained in at least 3 different ways.

First, the intuition trades on the *conflation between understanding the world and understanding the phenomena* – that point we made earlier.

Second, the intuition trades on the additional epistemic value that would be afforded by a correct explanation *if we knew it was the correct one*. Granted that piece of information would certainly be central to our planning and decisions concerning which strategies to pursue in our future research (if indeed one goal of the sciences is to find out the truth). Now, besides the fact that we are almost never in that epistemic situation, the problem is that being in the epistemic state of knowing that a given explanation is the correct one does not necessarily have anything to do with understanding. In fact, one could conceive of a case in which we are given the true theory for some phenomena P by some kind of alien, but we don't know how to navigate (or "grasp", as Strevens would have it) that explanation. In that case, we have a correct explanation without understanding. So, again, if we knew which of our explanations are true, it would change a lot of the scientific research landscape, but this is an issue that, by itself, is independent of whether or not our understanding of the phenomena would be increased.

Finally, the intuition trades on some confusion between different aims of scientific practice. It is possible that knowledge of correct explanations is the ultimate goal of science. That said, it does not follow from this that knowledge of correct explanations is the *only* aim of science, and that all epistemic value must be measured under the standard of that one, single aim. I would maintain that, even if we have knowledge of correct explanations, we might still gain in understanding of the phenomena (not of the world) if we learn how to navigate various alternative accounts for the phenomena. Let us say my ultimate goal is to run a marathon. That ultimate goal puts some constraint on my exercise regime, including running a non-negligible (and overall increasing) number of miles over the course of several months of training. That said, exercise affords other benefits in my life, such as stress relief, focus, and overall energy. It is not necessarily the case that reaching a fitness level that will allow me to actually meet my goal and run a marathon will also result in reaching the highest point for the other benefits. In fact, I can still gain in focus and stress relief from cross training. The point is that when pursuing different goals in engaging in an activity, not all goals need to be maximally fulfilled together or in the same way.

Overall, then, the intuition that correct explanations necessarily bring in the highest level of understanding is an understandably strong intuition. That said, it fails to stand up to serious scrutiny.

3.5. There is at least one other view, i.e. de Regt’s, that aims at being neutral towards the realism debate: how does modal understanding compare with it?

Henk de Regt has developed a well-articulated view of scientific understanding over the last ten years (de Regt 2009). de Regt’s main target is the “objectivist” view of understanding. His main claim is that scientific understanding necessarily has a pragmatic component, something excluded by objectivist views. De Regt’s view is as follows (de Regt, 2009, 593):

CUP [Criterion for Understanding Phenomena]: A phenomenon is understood scientifically iff a theory T of P exists that is intelligible (and the explanation of P by T meets accepted logical and empirical requirements).

A theory is intelligible by scientists if they know how to use it to generate models.

Note that de Regt makes no claims that the theory one uses or the models that one constructs with the theory to recover the phenomenon have to represent the world adequately in any way whatsoever. That said, there are no claims made that theories or models that accurately represent the world cannot be used to understand the phenomena. So, de Regt's concept of understanding seems suitably neutral with respect to the issue of realism.

How does de Regt's view compare to the modal view? Just as with the simple view (3.3), it seems to me that the two views are likely to be compatible, but that the modal view goes beyond de Regt's view.

The two views are compatible under a few assumptions. First, instances of first-level modal understanding will count as instances of understanding under de Regt's view, under the following assumption: if one knows how to navigate the dependency structures described by a theory, then one will be able to use the theory for model construction. If that's correct, then the first-level modal understanding is sufficient for understanding à la de Regt.

What about the other way around? Instances of understanding à la de Regt will qualify as instances of modal understanding only under the following assumption: that being able to use a theory to build models for the target phenomena is always deeply rooted in knowing how to navigate the possibility space for the phenomena, i.e. deeply rooted in modal understanding (at some or several level(s)). This seems to be a reasonable assumption, especially given how comprehensive the notion of modal understanding is: there is no easy model construction without some ability to navigate the possibility space, at least at the first level.

Now, one difference as I see it between the two views may be conceived the difference between an operational vs an intrinsic characterization of scientific understanding. While de Regt gives us a criterion (and actually also a test later on in the paper) by which to recognize scientific understanding, the modal view tries to characterize its nature. Another difference is that de Regt focuses on scientific understanding of a phenomenon via one theory, while the modal view consider how understanding is enriched by relating not to a single dependency structure described by a single theory but to the many dependency structures inhabiting the possibility space. Finally, the modal view makes better sense of why understanding some phenomena scientifically has not only some intrinsic epistemic value, but also some heuristic, value. It is not clear how the facilitation of model construction on the basis of a single theory affords heuristic value.

3.6 Isn't the view too permissive?

One might worry that anything goes on the modal view of understanding. Many things do indeed go under the modal view, but these things generally afford vastly different degrees of understanding. Two worries seem to come up here: (1) the case of theories like Creationism and Intelligent Design, (2) the case of ad hoc theories.

In the case of Creationism and Intelligent Design, the answer is pretty straightforward: these theories do not recover much of the phenomena, and hence, they do not afford much understanding as a result. Additionally, they do not bear interesting relations to other theories, nor do they tell us anything about the boundaries of the possibility space.

Let us turn to the case of ad hoc theories. These are theories that have required a number of special assumptions or modifications that were specifically assumed or added to allow the theory to recover otherwise recalcitrant phenomena. Creationism and Intelligent Design are examples of highly ad hoc theories. To set this discussion apart from the discussion above, let us consider a theory which has high recovery power, but it requires an array of auxiliary hypotheses which are not systematically related to the theory or to each other except insofar as they are just what it takes to have recovery take place. In such a case, the dependency structures associated with the theory afford less navigating power than a non ad hoc theory with similar overall recovery power. The reason why is that in these kinds of cases, the dependency structures associated with the ad hoc theory are to be inadequate to recover the phenomena without some additional contingencies not systematically related to the theory. When a theory isn't ad hoc, the theory itself provides the relevant resources to recover the phenomena. Hence, non ad hoc theories afford more navigating power to their ad hoc rivals, and hence will afford more modal understanding.

Conclusion

In this paper, we articulated a novel notion of scientific understanding: modal understanding. Modal understanding of some phenomena is afforded when one knows how to navigate the possibility space for these phenomena. It is a comprehensive notion that includes the extant notions of scientific understanding as special cases (under some reasonable assumptions), but also goes far beyond them. The modal view offers a notion of understanding that is afforded by theories and associated models that we know misrepresent the world. It is, as such, suitably neutral towards the debate over scientific realism. Modal understanding is not only understanding of the inner workings of a theory: it is a genuine form of understanding of the phenomena. The notion also explains why and how theories and associated models that we know misrepresent the world have both intrinsic epistemic value and heuristic value.

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[i] It is our belief that such TAMs are pervasive in pretty much all of the sciences. That said, there is no need to support such a claim for the purposes of this paper. It should be sufficient to consider some of the most striking and non-controversial examples, such as TAMs that misrepresent the world in ecology or economics for example. There is an extended literature on "false models" in (theoretical) ecology and how difficult it is to account for their epistemic value (a good starting point is Cooper (2003) in which one will find a review of the different ways in which theoretical modeling in ecology has been criticized and/or defended). As for economics, the work of Julian Reiss is quite relevant (Reiss 2012a, 2012b, 2013).

[ii] There have been a few attempts at relaxing the concept of explanation by weakening the requirement that the explanans statements be true. See Bokulich (2011) and Reiss (2012a) for recent discussions.

[iii] Woodward and Bogen originally introduced the distinction between phenomena and data in their 1988 article. Since then, they have defended the distinction on various occasions, one of the latest being Woodward (2011). See also van Fraassen (2008) for a distinction between phenomena, appearances, data models, and surface models.

[iv] Woodward and Bogen would here say that TAMs are meant to *explain* the phenomena in systematic ways. In order to preserve neutrality towards the debate over scientific realism, it is appropriate to restrict ourselves to the claim that they *account for* the phenomena in systematic ways. At this point, there is no need to decide on whether they (accurately) explain, or merely "save" the phenomena.

[v] There is no need within the confines of this paper to take a stance on what causal relations consist of, or even on whether or not the notions of cause and effect are useful in the sciences.

[vi] The literature on top-down influences is abundant. Among the advocates of the existence of top-down influences are Bishop (2008) and John Campbell (2009, 2010). Among the opponents are Kim (2000) and Craver and Bechtel (2007).

[vii] Obviously, a dependency structure in a (possible) world and the *description* of that structure in our TAMs are very different kinds of things. That said, it will often be very convenient to *refer* to a dependency structure in a (possible) world via the *description* we make of it in some of our TAMs.

[viii] Note that such a situation is not specific to the quantum domain. For some examples of incompatible but empirically equivalent theories in the classical domain, see Werndl (2013).

[ix] Equivocation should be avoided. When we speak of possible worlds associated with a set of phenomena, we have something like Lewisian possible world in mind.

When we speak of an emergent world, we mean a part or aspect of a single possible Everettian world. In an Everettian possible world there will typically be many emergent worlds that are associated with it.

[x] This is at least the case in David Wallace's functionalist understanding of EQM (Wallace, 2012).

[xi] See Goldstein (2013) for a very clear presentation of Bohmian Mechanics.

[xii] Among those who have recently argued that know-how is a kind of knowledge are Grimm (2006, 2014), Stanley (2011), and Khalifa (2012). Among those who argue (each for distinct reasons) that it is not are Zagzebski (2001), Kvanvig (2003), and Pritchard (2009, 2014).

[xiii] The notion of modal understanding has a lot to do with counterfactual reasoning, and the ability to answer w-questions. How exactly they relate to one another is beyond the scope of this paper.

[xiv] The literature on Bell theorems is plentiful. Bell's papers are indispensable references. They are reprinted in Bell (1987), with some additional ones in the second edition (Bell, 2004). For a recent synthesis, see Shimony (2005).

[xv] It seems that the most likely answer would be along these lines: TAMs that misrepresent the world do so partially. That means that they partially represent the world well. Their epistemic value consists in unveiling a piece of the truth. Their heuristic power is derived from that epistemic value. It would take another paper to fully address this issue, but here a quick answer: the problem with the proposal above is that we are most often *not* in an epistemic position to tell which parts of the TAMs are adequate, and which are not. Now it seems that heuristic power should be characterized by progress-promoting epistemic properties or dispositions that are accessible to us here and now, so that we can use them to advance towards our goals. Partial truth does not seem to fit the bill.